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Core-Temperature Sensor Ingestion Timing and Measurement Variability

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Context: Telemetric core-temperature monitoring is becoming more widely used as a noninvasive means of monitoring core temperature during athletic events.

Objective: To determine the effects of sensor ingestion timing on serial measures of core temperature during continuous exercise.

Design: Crossover study.

Setting: Outdoor dirt track at an average ambient temperature of 4.4°C ± 4.1°C and relative humidity of 74.1% ± 11.0%.

Patients or Other Participants: Seven healthy, active participants (3 men, 4 women; age = 27.0 ± 7.5 years, height = 172.9 ± 6.8 cm, body mass = 67.5 ± 6.1 kg, percentage body fat = 12.7% ± 6.9%, peak oxygen uptake [$\dot{V}O_{2peak}$] = 54.4 ± 6.9 mL•kg^{-1}•min^{-1}) completed the study.

Intervention(s): Participants completed a 45-minute exercise trial at approximately 70% $\dot{V}O_{2peak}$. They consumed core-temperature sensors at 24 hours (P1) and 40 minutes (P2) before exercise.

Main Outcome Measure(s): Core temperature was recorded continuously (1-minute intervals) using a wireless data logger worn by the participants. All data were analyzed using a 2-way repeated-measures analysis of variance (trial × time), Pearson product moment correlation, and Bland-Altman plot.

Results: Fifteen comparisons were made between P1 and P2. The main effect of time indicated an increase in core temperature compared with the initial temperature. However, we did not find a main effect for trial or a trial × time interaction, indicating no differences in core temperature between the sensors (P1 = 38.3°C ± 0.2°C, P2 = 38.3°C ± 0.4°C).

Conclusions: We found no differences in the temperature recordings between the 2 sensors. These results suggest that assumed sensor location (upper or lower gastrointestinal tract) does not appreciably alter the transmission of reliable and repeatable measures of core temperature during continuous running in the cold.

Key Words: thermal response, continuous exercise, body temperature

Key Points

- The telemetric core-temperature sensors recorded consistent core-temperature data independent of the time of ingestion and the assumed location of the sensor in the lower gastrointestinal tract during continuous running in the cold.
- The wireless core-temperature sensors could give health care providers a reliable way to track core-temperature changes in athletes during sporting events and to respond more effectively to heat-related symptoms in at-risk participants.

The practical ability to monitor core body temperature might be critical in athletic settings where the probability for developing heat or cold illness is elevated[1] and athletic performance subsequently decreases.[2] The more common methods for measuring core temperature include pulmonary artery, esophageal, rectal, and temporal measurements, which are impractical in a sport or occupational setting. Each of these measurement techniques has different applications for various scenarios. Pulmonary arterial blood temperature is measured with insertion of a catheter into the right pulmonary artery.[3] Measuring esophageal temperature involves positioning a temperature probe in approximately the lower third of the esophagus.[4] Rectal measurements to determine core temperature involve the insertion of a sensor approximately 10 cm past the anal sphincter. Temporal measurement records the highest temperature from an infrared scan, presumably of the temporal artery.[5] Although this last method is the least invasive, Low et al[6] reported that temporal measurements can underestimate core temperature during athletic events. The goal of each measure is to associate distal temperature measurements with the blood temperature of the hypothalamus, which regulates blood flow to the periphery and shivering for control of body temperature.[7] Another goal of each measure is to monitor internal body temperature to avoid dangerous temperatures associated with illness.

A different method to monitor core temperature in field settings is with ingestible, wireless sensors. Currently, 2 major companies (HQ Inc, Palmetto, FL, and Respironics Inc, Bend, OR) have telemetric core-temperature sensors and data-logger systems. These systems incorporate an ingestible capsule that is about the size of a vitamin and transmits temperature measurements to an external data-logger system, in which they can be stored or monitored continuously. Currently, each sensor is costly ($35 to $50 per sensor), but over time they might become more cost effective, enabling more institutions to use them.[8] Researchers have validated the ingestible temperature sensor against both esophageal and rectal techniques using different modes (walking, running, and cycling) and intensity levels of activity.[9–12] McKenzie and Osgood[8]

Table. Participant Descriptive Data (Mean ± SD)

	Men (n = 3)	Women (n = 4)	Combined (n = 7)
Age, y	21.3 ± 2.3	30.8 ± 7.4	27.0 ± 7.5
Height, cm	177.5 ± 3.4	169.4 ± 6.8	172.9 ± 6.8
Body mass, kg	71.0 ± 5.7	64.8 ± 5.5	67.5 ± 6.1
Body fat, %	8.9 ± 5.9	16.3 ± 6.3	12.7 ± 6.9
Peak oxygen uptake, mL•kg^{-1}•min^{-1}	60.9 ± 1.2	49.6 ± 4.5	54.4 ± 6.9
Peak oxygen uptake, L•min^{-1}	4.3 ± 0.4	3.2 ± 0.7	3.7 ± 0.7
Speed at 70% peak oxygen uptake, m•s^{-1}	4.1 ± 0.3	3.5 ± 0.2	3.8 ± 0.4

specifically validated the VitalSense (Respironics Inc) telemetric monitoring system with a Jonah (Respironics Inc) core temperature sensor. The researchers showed no difference between rectal (37.0°C ± 0.2°C) and ingestible-sensor (37.0°C ± 0.2°C) measurements, reporting R^2 = 0.80 for all data points during activities of daily living over a 2-day measurement period.

As it spends more time in the gastrointestinal (GI) tract, a sensor might be less susceptible to the influence of beverage or food. Wilkinson et al[13] found that ingestion of cold water (5°C to 8°C) can affect the sensor temperature measurement for up to 8 hours after sensor ingestion. Gant et al[14] also discussed a possible 0.15°C difference in temperatures between advanced regions of the colon and rectum. Further research is necessary to understand measurement of core temperature along the GI tract.[15]

To our knowledge, no researchers have studied agreement of multiple sensor measurements at more than 11.5 hours after ingestion. Athletic events, such as twice-daily football practices and ultraendurance events, can last more than 12 hours. If an ingested sensor can transmit valid core-temperature readings up to 24 hours, this could be cost effective for athletic trainers and other medical personnel because fewer sensors would need to be ingested. Therefore, the purpose of our study was to evaluate the agreement of core-temperature sensors ingested 24 hours apart. We hypothesized that we would find no differences in core-temperature readings between sensors ingested 24 hours apart during a short-term running exercise.

METHODS

Participants

Seven recreationally active participants (3 men, 4 women) with no known health issues volunteered for the study (Table). Participants were involved in their own daily exercise routines, including moderate amounts of run training, rather than in formal training. Diet and over-the-counter drug use was not restricted or recorded. Participants maintained normal habits between trials and were instructed not to exercise for 12 hours before each trial. All participants provided informed consent, and the study was approved by the University of Montana Institutional Review Board for the Use of Human Subjects in Research.

Study Design

Initial Visit. Body density was determined using hydrostatic weighing and was converted to body fat percentage using the equations of Siri.[16] Hydrostatic measurements were taken on a calibrated scale (Exertech, La Crescent, MN) until 2 values within 100 g of each other were achieved. After hydrostatic weighing, participants performed a maximal graded exercise test on a Trackmaster treadmill (model TMX425C; Full Vision, Inc, Newton, KS) to determine peak oxygen uptake ($\dot{V}O_{2peak}$). Participants walked at 3.13 m•s^{-1} on a 1% grade, and speed increased 0.08 m•s^{-1} each minute. When a respiratory exchange ratio of 0.96 was attained, treadmill grade increased every minute by 2% until the participant reached volitional fatigue. Oxygen uptake was measured using a 2-way mouthpiece (series 2700; Hans Rudolph, Inc, Shawnee, KS) and a metabolic measurement system (model TrueOne 2400; ParvoMedics, Sandy, UT). Oxygen uptake was determined by analyzing expired gas and averaging it every 15 seconds. Gas and flow calibration of the metabolic measurement system was performed before each participant trial according to the manufacturer's directions. Peak oxygen uptake was determined by the highest 15-second average during the graded exercise test.

Experimental Trial. Each participant completed the exercise protocol 3 times. He or she ingested a preprogrammed Jonah telemetric sensor each day for 4 days. The sensor ingested 24 hours before the scheduled exercise trial was treated as P1. The sensor ingested 40 minutes before exercise was treated as P2 and was ingested with 180 mL of water and a food bar (Nutri-Grain; Kellogg Co, Battle Creek, MI) (Figure 1). The water and food were provided to promote sensor movement into the small intestine. Researchers tracked the sensors upon ingestion until core temperature moved from approximately 33.0°C to the typical 36.5°C to 37.0°C as the sensor reached the small intestine. The exercise trial was initiated 40 minutes after P2 ingestion. The sensors were programmed to a specific data logger (VitalSense) that each participant carried during the exercise trial. The VitalSense system in conjunction with the Jonah sensor can be programmed so that each sensor can be detected independently, enabling multiple sensors to be identified. The data logger was placed in a Neoprene (DuPont Performance Elastimers, LLC, Wilmington, DE) waist belt superior to the gluteus maximus and recorded average temperature readings from the sensor every minute for the duration of the exercise trial.

Participants completed a 5-minute, self-selected warm-up followed by 45 minutes of continuous outdoor running on a 440-yd (396-m) dirt track at a pace equivalent to approximately 70% $\dot{V}O_{2peak}$. The exercise trial was initiated at 6 AM. While participants were running, researchers predetermined split times based on participants' $\dot{V}O_{2peak}$ tests by using American College of Sports Medicine[17] equations and provided feedback to maintain exercise intensity near 70% $\dot{V}O_{2peak}$. Participants were not allowed

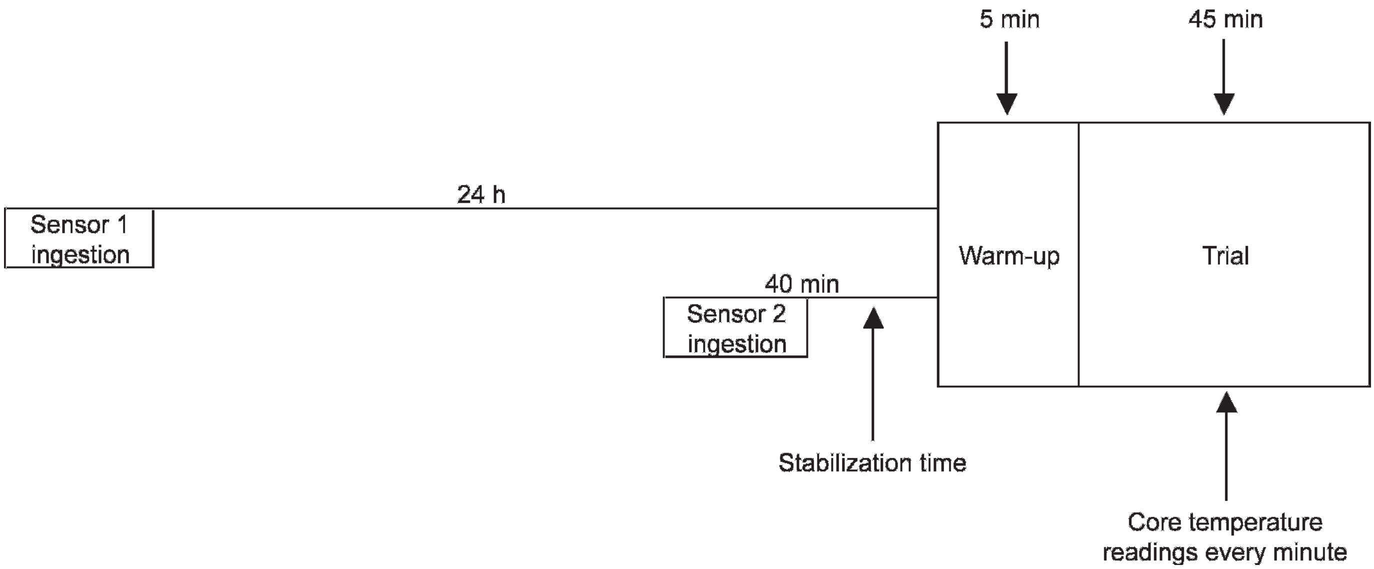

Figure 1. The experimental protocol was performed 3 times by each participant.

to consume any food or drink during the trial. Ambient dry temperature and humidity were recorded during the trial using a deluxe weather forecaster with atomic clock (model BAR388HGA-BK; Oregon Scientific, Portland, OR).

Statistical Analysis

Core temperatures were averaged at 5-minute intervals during the 45-minute exercise session for statistical comparisons. Core temperatures were compared between sensors and across exercise time using 2-way repeated-measures analyses of variance (ANOVAs). When a significant F ratio was found, the Bonferroni correction was applied to locate differences and correct for multiple comparisons. All ANOVAs were performed using SPSS (version 13 for Windows; SPSS Inc, Chicago, IL). A probability of type I error less than 5% was considered significant ($P < .05$). Data are reported as mean ± SD.

The Pearson product moment correlation was used to assess the relationship between sensors. A Bland-Altman plot with repeated measures was used to determine the limits of agreement between sensors.[18]

RESULTS

Ambient temperature and humidity during the trials were 4.4°C ± 4.1°C and 74.1% ± 11.0%, respectively. During 15 of 21 (71%) participant exercise sessions, both P1 and P2 transmitted data to the data logger. For the 6 (29%) instances in which P1 and P2 did not send signals, the sensor either had been excreted from the body (5 instances) or the data logger had lost the sensor's signal (1 instance). Sensors read 36.5°C to 37.0°C within 30 minutes after consumption.

We found a main effect for time ($F_{9,139} = 14.333$, $P < .001$). Multiple comparisons, including Bonferroni correction, indicated that each subsequent 5-minute segment was elevated compared with the initial temperature. We did not find a main effect for trial (P1 versus P2) ($F_{1,139} = 0.638$, $P = .44$) (Figure 2). For all time points, the average of P1 was 38.3°C ± 0.2°C (95% confidence interval [CI] = 38.16°C, 38.44°C) and of P2 was 38.3°C ± 0.4°C (95% CI = 38.09°C, 38.51°C). We did not find a time × trial interaction, indicating similar responses during the exercise trial regardless of capsule-ingestion timing ($F_{9,139} = 0.873$, $P = .48$). Pearson product moment correlation between P1 and P2 was $r = 0.99$ (Figure 3). The Bland-Altman limits of agreement for ±2 SDs were 0.56 and −0.50 with a mean bias of 0.04°C. Of the 150 temperature measurements, 139 (93%) were within ±2 SDs, and 109 (73%) of these were within ±1 SD (Figure 4).

DISCUSSION

Our data showed that the ingestion of temperature sensors 24 hours apart and, therefore, the assumed location in the lower GI did not affect measures of core temperature during continuous running. Our results were similar to those of Sparling et al,[12] who demonstrated that temperatures yielded by sensors ingested 3 to 4 hours before exercise and those ingested 8 to 9 hours before exercise were not different from rectal temperatures recorded during both cycling and running. Casa et al[19] compared oral, GI, axillary, aural, temporal, and on-the-field forehead measurements with rectal measurements before, during, and after team-sports exercise. They found that ingestible sensors were the only core-temperature measurement with no differences in temperature compared with rectal measurements at all time points.

Gant et al[14] showed a bias of an ingestible sensor (CorTemp; HQ, Inc) giving an elevated reading compared with the rectal sensor. Two other studies have yielded similar findings.[15,20] Although the average initial core temperature in our investigation was 37.9°C ± 0.4°C compared with the rectal norm of 37.6°C,[21] Gant et al[14] suggested that this might be explained, in part, by an absolute difference of 0.15°C between advanced regions of the colon and rectum, and our participants were warmed up slightly because they had walked to the laboratory.

In our study, there appear to be small but not statistically significant differences in the ingestible core-temperature sensor readings during the beginning of exercise (Figure 2). However, the average difference during this 5-minute interval was less than 0.1°C. The Bland-

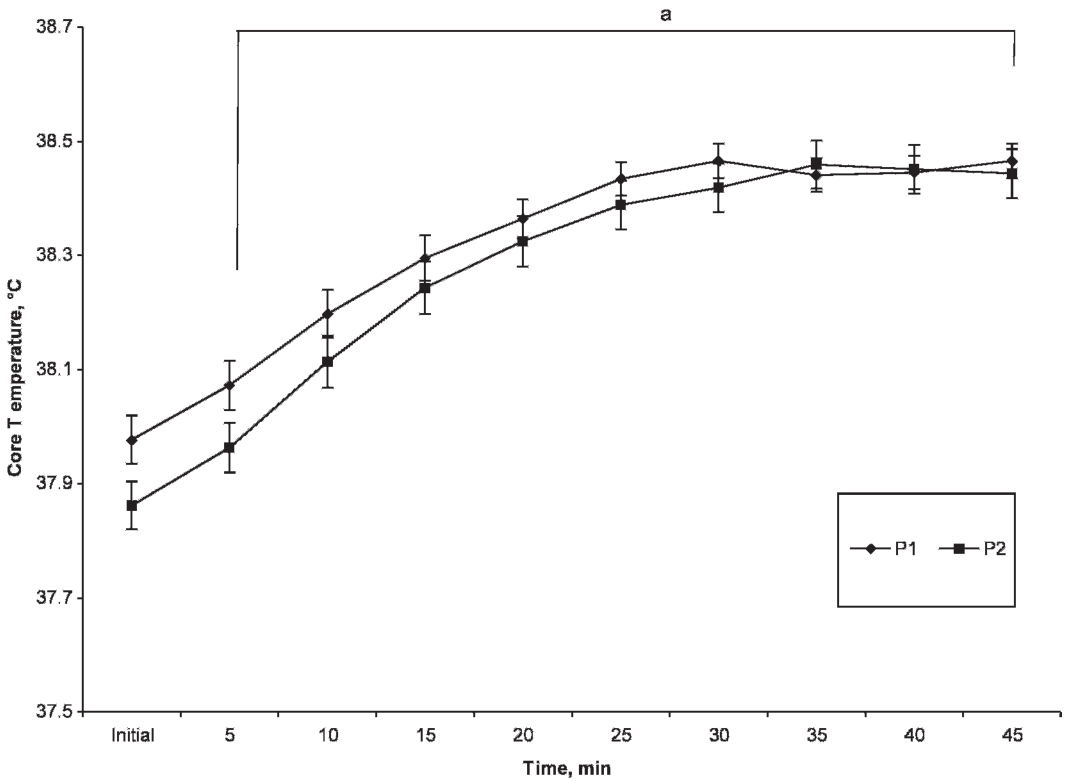

Figure 2. Core-temperature changes during exercise. We found no differences between the sensor ingested 24 hours (P1) and the sensor ingested 40 minutes (P2) before exercise (mean ± standard error of the mean). [a] Indicates that each 5-minute interval was elevated compared with the initial temperature (main effect for time) ($P < .05$).

Altman plot also demonstrated agreement between the sensors, with 95% of the comparisons within ±2 SDs and an average difference of 0.04°C (Figure 4). Figures 2 and 4 demonstrate that, as duration of activity increased, core temperature increased without a statistically significant difference between sensors. This is in agreement with Gant et al,[14] who concluded that when a steady-state temperature is reached, the accuracy of the core sensors increases.

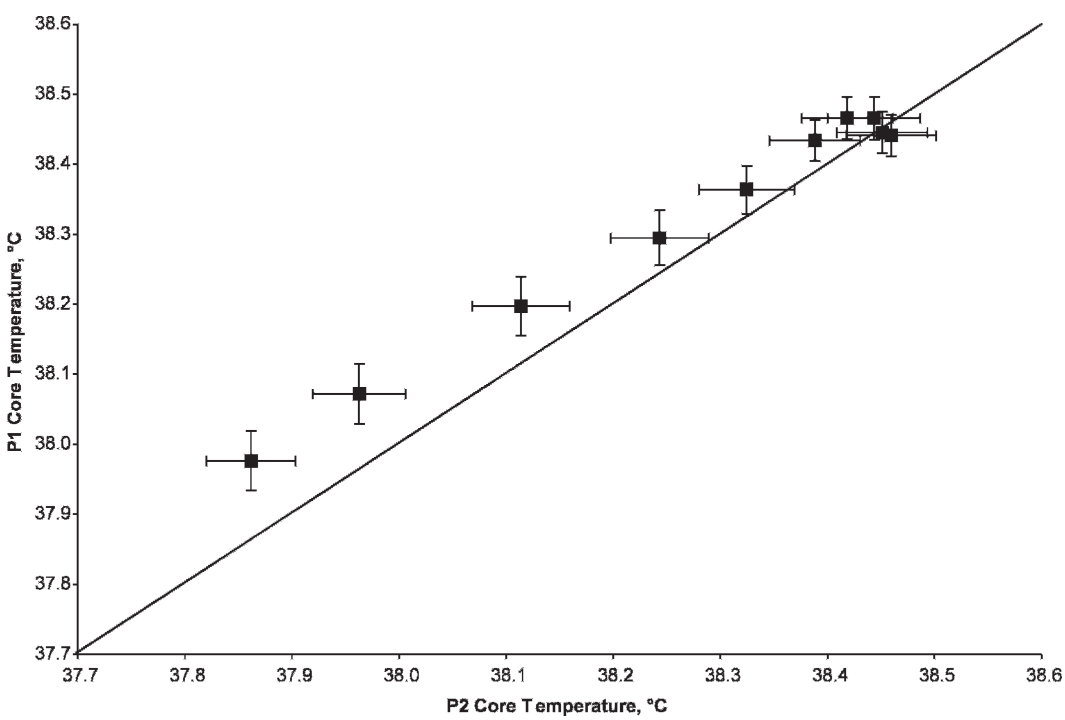

Figure 3. Pearson product moment correlation with the line of identity between the sensor ingested 24 hours (P1) and the sensor ingested 40 minutes (P2) before exercise. Each data point represents a 5-minute average ± standard error of the mean.

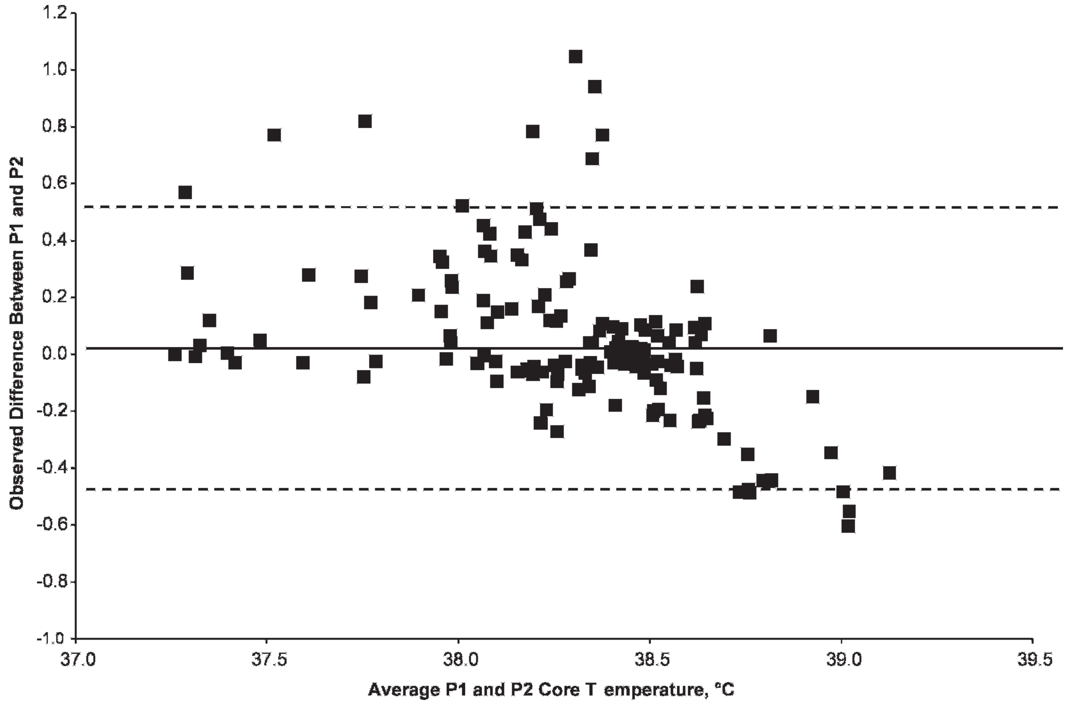

Figure 4. Bland-Altman plot of core-temperature readings during 45 minutes of continuous exercise. The solid line represents the mean average difference (0.047°C), and the dashed lines are 2 SDs from the mean.

This evidence suggests that a sensor ingested 24 hours before exercise and a sensor ingested shortly before exercise when no fluids are ingested during exercise transmit similar temperature data.

During our study, the sensor was excreted from the body within 24 hours in 5 instances, and 15 temperature points were not transmitted to the data logger in 1 instance. For the entire study, 1472 (16 trials with 2 sensors in the GI tract $\times$ 46 measurement points) total possible temperature readings were recorded, resulting in a 1.1% loss of temperature data due to equipment malfunction. This was less than the 3.1% loss reported by McKenzie and Osgood[8] in the validation of the sensor used. Researchers studying GI transit time have shown extreme variability depending on the individual. McKenzie and Osgood[8] reported from a half day to more than 5 days for sensor excretion. They found participants who consumed a larger bolus of food had decreased transit time. Keeling and Martin[22] also found that mild treadmill walking (1.6 $m \cdot s^{-1}$ at 2% grade) increased transit speeds of a liquid meal by 20% to 25%. The biggest threat to lost data appears to be excretion of the sensor rather than sensor malfunction.

Time for movement of the sensor from the stomach into the intestinal tract needs to be allowed for removal of the artificial temperature deviation due to stomach contents and consumption of fluid or food during activity. Heil and Ruby[23] found that average transit time of core-temperature sensors out of the stomach was 18.2 ± 2.5 minutes after a meal. Therefore, a standardized ingestion time might be warranted for core-sensor ingestion during short-term investigative procedures. In our study, 40 minutes were allowed for the movement out of the stomach, minimizing the risk of the sensor remaining in the stomach. To minimize the potential for the ingestion of fluids to create lower temperature readings in our study, participants did not consume any fluids 40 minutes before or during the running trial. Wilkinson et al[13] found that ingestion of cold water (5°C to 8°C) can affect the sensor temperature measurement for up to 8 hours after sensor ingestion. In these 2 studies,[13,23] researchers showed that a core-temperature sensor needs to be ingested no less than 20 minutes before a measurement period during which fluid is restricted or needs to be ingested at least 8 hours before a measurement period during which cold-fluid consumption is allowed.[13,23]

These devices might serve a practical purpose during sporting events characterized by intermittent exercise bouts, such as American football or soccer. These sports often are played during high ambient temperatures and humidity that put athletes at risk for heat-related illnesses.[1] A limitation of our study was that the exercise was continuous in cold-weather conditions, and telemetric sensors possibly respond differently under these circumstances. However, Gant et al[14] showed that an ingestible sensor was valid and reliable compared with a rectal measurement for core temperature during intermittent running, and Fowkes Godek et al[24] found no differences in core-temperature readings during continuous exercise with cross-country runners and during intermittent exercise in football players using ingestible sensors.

In our study, the ambient temperature was 4.4°C ± 4.1°C, which can lead to increased heat loss to the environment. This is increased further when the skin is wet from rain or sweat. Investigators have discussed the rate of rise or fall as a more appropriate indicator of potential temperature illness than the set limit of 40.0°C for hyperthermia and 35.0°C for mild hypothermia. Carter et al[25] showed data on how an individual had an "abnormal" rise in core temperature. The individual had cellulitis, and, after receiving treatment, core temperature returned to normal. O'Brien et al[11] showed that core-temperature sensors were valid at monitoring increasing core temperature and steady-state temperature. In a study with non–steady-state team sports consisting of soccer and ultimate Frisbee, Casa et al[19] found no differences between the rate of rise and decline of core-temperature measurements using ingestible core sensors and rectal temperatures, reporting an overall correlation of $r = 0.86$. A rectal thermometer is used in sporting events when an individual already has begun to demonstrate signs of heat or cold illnesses; however, using rectal thermometers in a field setting is not practical for continuously monitoring the rise or fall of core temperature, making ingestible sensors more practical for monitoring athletes during the event.

Wireless core-temperature sensors could give health care providers the advantage of tracking the core-temperature change and being able to respond more effectively to heat-related symptoms in at-risk participants. The VitalSense has a Medic Mode that enables it to acquire data from any sensor within its range (approximately 1 m). Each sensor is serial coded, and the data logger can identify the specific sensor signal. An advantage of the VitalSense is that each sensor has a unique signal identification to avoid cross-talk among sensors in the same participant or in close proximity and to enable the VitalSense to identify each sensor. This would enable athletic trainers and team physicians to track athletes during a game or practice and would permit early detection of an athlete who might be at risk for heat injury. Although outfitting each participant with a temperature capsule and monitor is not practical, athletes prone to heat-related illness or with known risk factors could be monitored more effectively with this equipment.

The telemetric temperature sensor has a practical application in most performance settings. Our data demonstrated no appreciable difference regardless of assumed location in the GI tract. In some instances, participants will not consume fluids during the critical monitoring period. However, fluid consumption is recommended during long-duration events in which heat-related illnesses are a risk. As mentioned, prior ingestion of fluids can affect the temperature measures obtained from a similar telemetric sensor for up to 8 hours after ingestion,[13] which suggests that sensor ingestion must occur well before an event. For example, if the event is scheduled for noon, sensor ingestion would have to occur at 4 AM according to these recommendations. Our results suggested that a competitor can ingest the sensor before going to bed and that the sensor will transmit valid data the next day.

CONCLUSIONS

Our data showed that a telemetric core-temperature sensor records consistent core-temperature data independent of ingestion time and the assumed location of the sensor in the lower GI tract during continuous running in the cold. It is valuable for health professionals to have reliable core-temperature measurements when monitoring athletes during sporting events. In the future, researchers should consider the effects of sensor location during noncontinuous exercise, which is more common in typical collegiate and professional sporting events, and during emergency response situations.

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